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# Observation of Z decays to four leptons with the CMS detector at the LHC

The CMS Collaboration\*

## Abstract

The first observation of the Z boson decaying to four leptons in proton-proton collisions is presented. The analyzed data set corresponds to an integrated luminosity of  $5.02 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$  collected by the CMS detector at the Large Hadron Collider. A pronounced resonance peak, with a statistical significance of  $9.7\sigma$ , is observed in the distribution of the invariant mass of four leptons (electrons and/or muons) with mass and width consistent with expectations for Z boson decays. The branching fraction and cross section reported here are defined by phase space restrictions on the leptons, namely,  $80 < m_{4\ell} < 100 \text{ GeV}$ , where  $m_{4\ell}$  is the invariant mass of the four leptons, and  $m_{\ell\ell} > 4 \text{ GeV}$  for all pairs of leptons, where  $m_{\ell\ell}$  is the two-lepton invariant mass. The measured branching fraction is  $\mathcal{B}(Z \rightarrow 4\ell) = (4.2_{-0.8}^{+0.9}(\text{stat.}) \pm 0.2(\text{syst.})) \times 10^{-6}$  and agrees with the standard model prediction of  $4.45 \times 10^{-6}$ . The measured cross section times branching fraction is  $\sigma(\text{pp} \rightarrow Z) \mathcal{B}(Z \rightarrow 4\ell) = 112_{-20}^{+23}(\text{stat.})_{-5}^{+7}(\text{syst.})_{-2}^{+3}(\text{lumi.}) \text{ fb}$ , also consistent with the standard model prediction of  $120 \text{ fb}$ . The four-lepton mass peak arising from  $Z \rightarrow 4\ell$  decays provides a calibration channel for the Higgs boson search in the  $H \rightarrow ZZ \rightarrow 4\ell$  decay mode.

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\*See Appendix A for the list of collaboration members



## 1 Introduction

We present the first observation of  $Z \rightarrow 4\ell$  decays in pp collisions at  $\sqrt{s} = 7$  TeV, and measurements of the production cross section times branching fraction for Z decays into four leptons  $\sigma(\text{pp} \rightarrow Z) \mathcal{B}(Z \rightarrow 4\ell)$  and the branching fraction  $\mathcal{B}(Z \rightarrow 4\ell)$ . In this paper,  $\ell$  denotes an electron or muon. Previously, all four LEP collaborations reported observations of final states with four fermions,  $e^+e^- \rightarrow 4f$ , which include  $e^+e^- \rightarrow Z \rightarrow 4f$  [1–4]. However, the observation of  $Z \rightarrow 4\ell$  decays in pp collisions is of special interest. The clean resonant peak in the four-lepton invariant mass distribution at  $m_{4\ell} = m_Z$  can be used for direct calibration of the four-lepton mass scale, the four-lepton mass resolution, and the overall four-lepton reconstruction efficiency in phase space similar to the light Higgs boson four-lepton decays,  $H \rightarrow ZZ \rightarrow 4\ell$ . The  $\text{pp} \rightarrow Z \rightarrow 4\ell$  process and its implications for the  $H \rightarrow ZZ \rightarrow 4\ell$  search at the Large Hadron Collider (LHC) were first studied in Ref. [5].

These results are based on the data collected in 2010 and 2011 by the Compact Muon Solenoid (CMS) detector [6] at the LHC. The data set used in the analysis corresponds to a total integrated luminosity of  $5.02 \pm 0.11 \text{ fb}^{-1}$ .

## 2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid 13 m in length and 6 m in diameter providing an axial magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Charged particle trajectories are measured by the tracker, covering  $0 < \phi < 2\pi$  in azimuth and  $|\eta| < 2.5$ , where the pseudorapidity is defined as  $\eta = -\ln[\tan(\theta/2)]$ , with  $\theta$  being the polar angle of the trajectory of the particle with respect to the anticlockwise beam direction. Muons are measured in the pseudorapidity range  $|\eta| < 2.4$ , with detection planes made using three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum ( $p_T$ ) resolution of about 2% in the muon  $p_T$  range relevant for the analysis presented in this paper (from a few to a few tens of GeV). The ECAL consists of nearly 76 000 lead tungstate crystals distributed in the barrel region (EB,  $|\eta| < 1.479$ ) and two endcap regions (EE,  $1.479 < |\eta| < 3$ ), and has an ultimate energy resolution better than 0.5% for unconverted photons with transverse energies above 100 GeV. The electron energy resolution is 3% or better for the range of energies relevant for the measurement reported in this paper. A two-level trigger system selects the most interesting events for use in the offline physics analyses. A more detailed description of the CMS detector can be found in Ref. [6].

## 3 Signal definition

The leading-order (LO) Feynman diagram for the Z production and decay into four leptons,  $q\bar{q} \rightarrow Z \rightarrow 4\ell$ , is presented in Fig. 1 (left). This process is sometimes referred to as single-resonant four-lepton production.

We define signal events as those with four leptons,  $e^+e^-e^+e^-$  (4e),  $\mu^+\mu^-\mu^+\mu^-$  (4 $\mu$ ), or  $e^+e^-\mu^+\mu^-$  (2e2 $\mu$ ), with four-lepton invariant mass satisfying  $80 < m_{4\ell} < 100 \text{ GeV}$  and dilepton masses  $m_{\ell\ell} > 4 \text{ GeV}$  for all six possible pairings of leptons. The lower limit on  $m_{\ell\ell}$  reduces background that rises rapidly as  $m_{\ell\ell}$  decreases. The branching fraction and cross section reported here are defined by these phase space restrictions.

Predicted partial widths and branching fractions for  $Z$  boson decays to  $4e$ ,  $4\mu$ , and  $2e2\mu$  final states are summarized in Table 1. The results are obtained at LO using CalcHEP 3.2 [7], which takes quantum mechanical interferences into account. The partial width for the  $2e2\mu$  channel is different from twice the width in either the  $4e$  or  $4\mu$  channel because decays to four leptons of the same flavour involve additional Feynman diagrams with permutations of same-sign leptons. We do not have a sufficient number of events to measure the differences between decay rates for the three four-lepton final states. We therefore measure the overall branching fraction  $\mathcal{B}(Z \rightarrow 4\ell)$  and assume the  $4e$ ,  $4\mu$ , and  $2e2\mu$  relative branching fractions predicted by theory (Table 1). The main irreducible background is the process  $q\bar{q} \rightarrow Z\gamma^* \rightarrow 4\ell$ , for which the LO Feynman diagram is shown in Fig. 1 (right). Events are simulated with the next-to-leading-order generator POWHEG [8]. The effects of multiple pp collisions within each bunch crossing are taken into account in all simulated samples.

Table 1: Partial widths and branching fractions for  $Z$  boson decays to  $4e$ ,  $4\mu$ ,  $2e2\mu$  final states with  $m_{\ell\ell} > 4$  GeV for all lepton pairs. The branching fractions are calculated with CalcHEP 3.2 [7] at LO using the total  $Z$  boson width  $\Gamma_{\text{tot}} = 2.4952$  GeV [9]. Theoretical uncertainties are smaller than experimental uncertainties and are not shown in the table.

Quantity of interest	$4e$	$4\mu$	$2e2\mu$	$4\ell$
Partial width, $\Gamma_i$ (keV)	2.95	2.95	5.21	11.12
Branching fractions, $\Gamma_i/\Gamma_{\text{tot}}$	$1.18 \times 10^{-6}$	$1.18 \times 10^{-6}$	$2.09 \times 10^{-6}$	$4.45 \times 10^{-6}$
Relative fractions, $f_i = \Gamma_i/\Gamma_{4\ell}$	0.2655	0.2655	0.4690	-

## 4 Signal extraction

The trigger and selection criteria used in this analysis closely follow the  $H \rightarrow ZZ \rightarrow 4\ell$  search by CMS [10]. We use data collected with dielectron and dimuon triggers selecting events with at least two electrons or two muons with transverse momentum  $p_T > 17$  and 8 GeV. To match the trigger selection, we require that at least two leptons reconstructed offline have  $p_T > 20$  and 10 GeV. In this phase-space region, we expect and observe a high trigger efficiency of 96–99%, depending on the final state.

Muon candidates are reconstructed using two algorithms, one in which tracks in the silicon strip tracker are matched to hits in the muon detectors, and another in which a combined fit is performed to signals in both the silicon strip tracker and the muon system [11]. The muon

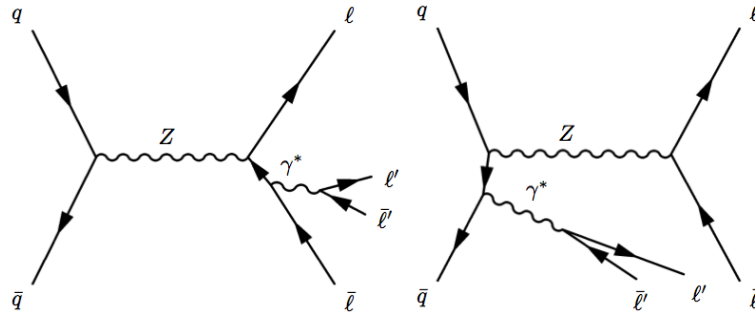


Figure 1: (Left) Diagram of the  $Z \rightarrow 4\ell$  process. (Right) Diagram of the  $Z\gamma^* \rightarrow 4\ell$  process for the irreducible background of  $Z \rightarrow 2\ell$  production with the initial-state radiation undergoing an internal conversion  $\gamma^* \rightarrow 2\ell$ . Both  $Z$  and  $\gamma^*$  are present in all propagators. The choice of propagators shown in the figures corresponds to the dominant contributions in the phase space  $80 < m_{4\ell} < 100$  GeV.

candidates are required to be successfully reconstructed by both algorithms. Other identification criteria (the number of measurements in the tracker and muon systems, the fit quality of the muon track, and the consistency of the track with the primary vertex) are also imposed on the muon candidates to reduce the misidentification rate. The vertex with the largest value of  $\sum p_T^2$  for the associated tracks is chosen to be the primary vertex. According to simulation, this requirement provides the correct assignment for the primary vertex in more than 99% of both signal and background events. The average number of reconstructed vertices per event in 2011 data is approximately 7.

Electron reconstruction also involves two algorithms, one in which energy clusters in the electromagnetic calorimeter are matched to signals in the silicon pixel detector and another in which tracks in the silicon strip tracker are matched to ECAL clusters [12]. The electron candidates used in the analysis are reconstructed by either algorithm. Additional identification criteria (the spatial distribution of the shower in the ECAL, matching of the electron track with a cluster in the ECAL, and consistency of the track with the primary vertex) are imposed on the electron candidates to reduce the misidentification rate. Requirements are imposed on the geometrical properties of the electron track with respect to the primary vertex and neighbouring tracks, as well as requirements on the number of missing hits in the innermost tracker layers in order to remove electrons produced by photon conversions in the detector material.

Electrons are required to satisfy  $p_T > 7$  GeV and  $|\eta| < 2.5$ , while muons are required to satisfy  $p_T > 5$  GeV and  $|\eta| < 2.4$ .

Leptons produced in the decay of Z (or  $\gamma^*$ ) bosons are typically isolated from hadronic activity in the event. The scalar sum of transverse energy deposits in the calorimeters and the transverse momenta of tracks in a cone of radius  $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$  in  $\eta$ - $\phi$  space around each lepton is computed. This sum is corrected for the contribution from the other lepton candidates as well as for the average hadronic activity in an event. The ratio of this corrected sum to the lepton  $p_T$  is required to be smaller than 0.275.

To suppress background events with leptons originating from secondary vertices (such as heavy quark decays or misidentified pions), the significance of the impact parameter of each lepton relative to the primary vertex,  $s_{3D} = d_{3D}/\sigma_{3D}$ , is required to satisfy  $|s_{3D}| < 4$ , where  $d_{3D}$  is the impact parameter in three dimensions and  $\sigma_{3D}$  is its associated uncertainty.

Events are selected with at least four leptons satisfying the above criteria. The same-flavour, opposite-charge lepton pair with mass closest to the nominal Z boson mass is identified. A second pair is constructed from the remaining leptons with the highest  $p_T$  satisfying the requirement of the same flavour and opposite charge. We require all six dilepton combinations constructed from the four selected leptons to satisfy  $m_{\ell\ell} > 4$  GeV and the four-lepton invariant mass must be in the range  $80 < m_{4\ell} < 100$  GeV. The overall reconstruction and selection efficiencies for simulated signal events are found to be 25%, 59%, and 33% for the  $4e$ ,  $4\mu$  and  $2e2\mu$  channels, respectively. The overall theoretical acceptance efficiencies (per channel, in the same order) are 8.9%, 14%, and 11.1%.

We estimate the irreducible four-lepton background from simulation using selection efficiencies corrected for differences between the simulated efficiencies and those measured in data.

Processes with one or more misidentified or nonprompt leptons contributing to the signal region  $80 < m_{4\ell} < 100$  GeV are dominated by Z + X production. Their rate is measured in data using control regions and is found to be negligible. The methodology used is identical to that used in the  $H \rightarrow ZZ \rightarrow 4\ell$  search [13].

We use  $pp \rightarrow Z \rightarrow 2\mu$  events as a control sample in order to cancel systematic uncertainties in the measurement of the branching fraction  $\mathcal{B}(Z \rightarrow 4\ell)$ . The muon selection criteria are identical to those in the  $Z \rightarrow 4\ell$  event selection with  $p_T$  thresholds  $p_T > 20$  and  $10$  GeV applied to the higher and lower  $p_T$  muons, respectively.

## 5 Results

### 5.1 Observation of $Z \rightarrow 4\ell$ decays

Figure 2 shows the four-lepton mass distribution for events that pass all the selection criteria except the invariant mass requirement. Events with all three final states,  $4e$ ,  $4\mu$ , and  $2e2\mu$ , are included. The prominent peak at  $m_{4\ell} = m_Z$  constitutes the first observation of  $pp \rightarrow Z \rightarrow 4\ell$ . The number of events with  $80 < m_{4\ell} < 100$  GeV is 28, in good agreement with the standard model expectation of 30.0 events. Table 2 shows good agreement between the expected and observed events in each of the  $4e$ ,  $4\mu$ , and  $2e2\mu$  channels. The probability for a background fluctuation to be at least as large as the observed maximum excess can be evaluated by generating sets of simulated data incorporating all statistical and systematic uncertainties. This probability can be expressed as a corresponding number of standard deviations using the one-sided Gaussian tail convention. The results presented in this paper are obtained using asymptotic formulae [14] and include the systematic uncertainties described in the next subsection. The statistical significance of the peak in Fig. 2 is  $9.7\sigma$ .

Table 2: Numbers of expected and observed events. The yields are determined by means of fits described in the text; the fit results in the  $4e$  channel are not meaningful because only two events are selected.

Final state channels	$4e$	$4\mu$	$2e2\mu$	$4\ell$
Irreducible background ( $pp \rightarrow Z\gamma^* \rightarrow 4\ell$ )	0.07	0.25	0.14	$0.46 \pm 0.05$
Other (reducible) backgrounds	0.01	0.01	0.05	$0.07 \pm 0.1$
Expected signal ( $pp \rightarrow Z \rightarrow 4\ell$ )	3.8	13.6	12.0	$29.4 \pm 2.6$
Total expected (simulation)	3.9	13.9	12.2	$30.0 \pm 2.6$
Observed events	2	14	12	28
Yield from fit to the observed mass distribution	-	$13.6 \pm 3.8$	$11.5 \pm 3.1$	$27.3 \pm 5.4$

### 5.2 Measurement of $\sigma(pp \rightarrow Z) \mathcal{B}(Z \rightarrow 4\ell)$ and $\mathcal{B}(Z \rightarrow 4\ell)$

The numbers of  $Z \rightarrow 4\ell$  (signal) and  $Z \rightarrow 2\mu$  (control) events passing the selection may be expressed as follows:

$$N^{4\ell} - N_{\text{bkg}}^{4\ell} = \sum_i L \sigma(pp \rightarrow Z) \mathcal{B}(Z \rightarrow 4\ell) f_i \epsilon_i^{\text{acc}} \epsilon_i^{\text{exp}} c_i \quad (i = 4e, 4\mu, 2e2\mu), \quad (1)$$

$$N^{2\mu} - N_{\text{bkg}}^{2\mu} = L \sigma(pp \rightarrow Z) \mathcal{B}(Z \rightarrow 2\mu) \epsilon_{Z \rightarrow 2\mu}^{\text{acc}} \epsilon_{Z \rightarrow 2\mu}^{\text{exp}} c_{Z \rightarrow 2\mu}, \quad (2)$$

where

- $L$  denotes the integrated luminosity;
- $\sigma(pp \rightarrow Z) = 26.9$  nb is the theoretical  $Z$  boson production cross section ( $80 < m_{4\ell} < 100$  GeV), calculated with FEWZ [15] at NNLO level;
- $\mathcal{B}(Z \rightarrow 4\ell)$  is the signal decay branching fraction (for  $m_{\ell\ell} > 4$  GeV);

- $\mathcal{B}(\text{Z} \rightarrow 2\mu) = 0.03366 \pm 0.00002$  is the  $\text{Z} \rightarrow 2\mu$  branching fraction [9];
- $f_i$  is the relative fraction of all  $4\ell$  events in the  $i$ th channel ( $i = 4e, 4\mu, 2e2\mu$ ) from Table 1;
- $\epsilon_i^{\text{acc}}$  is the theoretical acceptance of the lepton  $p_T$  and  $\eta$  requirements used in the analysis;
- $\epsilon_i^{\text{exp}}$  is the experimental efficiency, as obtained from the simulation, to reconstruct events within the acceptance;
- $c_i$  is the data-to-simulation correction factor for the experimental efficiency derived from Monte Carlo events. The  $c_i$  are within one percent of unity.

Equation (1) allows the extraction of the production cross section times branching fraction  $\sigma(\text{pp} \rightarrow \text{Z}) \mathcal{B}(\text{Z} \rightarrow 4\ell) = 112_{-20}^{+23} (\text{stat.}) \text{fb}$ , while the ratio of Eqns. (1) and (2) allows extraction of the branching fraction  $\mathcal{B}(\text{Z} \rightarrow 4\ell) = (4.2_{-0.8}^{+0.9} (\text{stat.})) \times 10^{-6}$  with cancellation of several systematic uncertainties.

The signal and the irreducible background have the following systematic uncertainties:

- Interference between the signal and background production is less than 0.2% in the range  $80 < m_{4\ell} < 100 \text{ GeV}$ , and is accounted for as a source of systematic uncer-

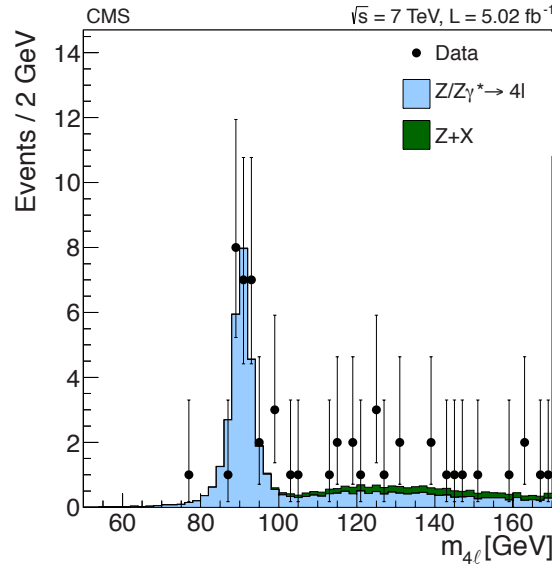


Figure 2: Four-lepton invariant mass distribution for events passing all selection requirements except that on  $m_{4\ell}$ . The data are shown by points. The filled histograms represent standard model expectations for  $\text{pp} \rightarrow \text{Z}/\text{Z}\gamma^* \rightarrow 4\ell$  and for reducible backgrounds. The three final states,  $4e$ ,  $4\mu$ , and  $2e2\mu$ , are combined.

tainty.

- Uncertainties in parton distribution functions lead to uncertainties in the total cross section and acceptance. For  $pp \rightarrow Z\gamma^* \rightarrow 4\ell$  and  $pp \rightarrow Z \rightarrow 2\mu$ , these uncertainties are 4% [10] and 1% [16]. For  $pp \rightarrow Z \rightarrow 4\ell$  we obtain an uncertainty of 4% by following the same procedure as in Ref. [10].
- The theoretical uncertainties related to the choice of QCD renormalization/factorization scales are evaluated by varying these scales up and down by a factor of two. For  $pp \rightarrow Z\gamma^* \rightarrow 4\ell$  and  $pp \rightarrow Z \rightarrow 2\mu$ , these uncertainties are both 2% [10, 16]. For  $pp \rightarrow Z \rightarrow 4\ell$  we obtain an uncertainty of 1% by following the same procedure as in Ref. [10].
- The effect of bremsstrahlung radiation on event acceptance is estimated to be negligible.
- Lepton reconstruction, isolation, and impact parameter uncertainties as well as uncertainties associated with the high-level trigger efficiency are determined using a “tag-and-probe” method [16] where efficiencies and uncertainties are measured in samples of  $Z \rightarrow 2\ell$  events. The statistical uncertainties on the lepton efficiencies obtained in different ( $p_T$ ,  $\eta$ ) bins are propagated to four-lepton reconstruction uncertainties for  $Z \rightarrow 4\ell$  and  $Z\gamma^* \rightarrow 4\ell$  events. These uncertainties range from 1% to 6%. Correlation between the “tag-and-probe” efficiency measurement at the  $Z \rightarrow 2\ell$  calibration signal are taken into account.
- The uncertainty on the integrated luminosity is 2.2% [17].

The reducible background is estimated directly from data. The predicted yield of the reducible backgrounds is approximately 0.1 event (less than one percent of the signal yield, as shown in Table 2) and has a total uncertainty, also evaluated from data, of 130%.

To account for systematic uncertainties, including correlations among different channels, as well as between signal and background, we construct the likelihood for the four observed final states ( $4e$ ,  $4\mu$ ,  $2e2\mu$ , and  $2\mu$ ). Using the full likelihood in conjunction with the profile likelihood method [14], we measure the production cross section times branching fraction and the branching fraction for  $Z \rightarrow 4\ell$  to be

$$\begin{aligned}\sigma(pp \rightarrow Z) \mathcal{B}(Z \rightarrow 4\ell) &= 112^{+23}_{-20} (\text{stat.})^{+7}_{-5} (\text{syst.})^{+3}_{-2} (\text{lum.}) \text{ fb}, \\ \mathcal{B}(Z \rightarrow 4\ell) &= (4.2^{+0.9}_{-0.8} (\text{stat.}) \pm 0.2 (\text{syst.})) \times 10^{-6}.\end{aligned}$$

These measurements agree with the standard model predictions,  $120 \pm 5 \text{ fb}$  and  $4.45 \times 10^{-6}$ , respectively.

### 5.3 $Z \rightarrow 4\ell$ decays as a calibration channel in the $H \rightarrow ZZ \rightarrow 4\ell$ search

The  $Z \rightarrow 4\ell$  decays give a narrow resonant peak in the four-lepton invariant mass distribution, which can be used as a calibration channel in the context of the Higgs boson search in the  $H \rightarrow ZZ \rightarrow 4\ell$  decay mode. Figure 3 (left) shows that the number of events in the  $Z \rightarrow 4\ell$  peak at  $m_{4\ell} = m_Z$  is approximately an order of magnitude larger than the expected number of events for the SM Higgs boson with a mass  $m_H = 125 \text{ GeV}$  [13, 18]. The  $Z \rightarrow 4\ell$  peak can be used for a direct calibration of the four-lepton mass scale, the four-lepton mass resolution, and the overall four-lepton reconstruction efficiency in a phase space similar to the Higgs boson four-lepton decays. Such a direct calibration using the  $Z \rightarrow 4\ell$  peak is complementary to the current



indirect tag-and-probe method making use of  $Z \rightarrow 2\ell$  events, with the benefit that  $Z \rightarrow 4\ell$  has similar kinematics to  $H \rightarrow ZZ \rightarrow 4\ell$ .

Figure 3 (right) shows the results of an unbinned maximum-likelihood fit to the four-lepton mass distribution for the observed events. The fitted signal yield is shown in the last line of Table 2, along with the results of separate fits to the mass distributions in the three channels. The background shape comes from a simulation of  $pp \rightarrow ZZ \rightarrow 4\ell$  events with the overall normalization floating in the fit. Differences in shape between the reducible and irreducible backgrounds are ignored because of the small contribution of the former. The signal shape is a convolution of the Breit–Wigner and Crystal Ball [19] functions. The central value and width of the Breit–Wigner function are fixed at the  $Z$  boson mass and width [9]. The Crystal Ball parameters are free to vary in the fit. Data used for this analysis is only a (lower energy) subset of that used in the recent discovery paper [13].

From the fit results, as shown in Fig. 3 (right), one can see that the offset of the peak is  $0.4 \pm 0.4$  GeV (the “mean” value of the Crystal Ball function represents an offset with respect to the fixed Breit–Wigner function peak position), or, in relative units,  $0.4 \pm 0.4\%$ . These numbers can be used to constrain the possible systematic uncertainty of the four-lepton mass scale. With the current data there is no evidence for a statistically significant bias.

The Crystal Ball width (sigma of the Gaussian core) returned by the fit is  $1.1 \pm 0.5$  GeV, consistent with the simulation-based expectations of 1.0% for  $4\mu$  and 1.4% for  $2e2\mu$  (which for a Higgs boson with mass 125 GeV corresponds to 1.3 GeV and 1.8 GeV) for a Higgs signal in this mass range. There are only two  $4e$  events, so the mass resolution of  $4e$  events cannot be constrained. With the current data, we can measure the average four-lepton mass resolution with about 45% statistical uncertainty.

## 6 Summary

The first observation of the  $Z$  boson decaying to four leptons (electrons and/or muons) in proton-proton collisions has been presented. The data set analyzed corresponds to an integrated luminosity of  $5.02 \text{ fb}^{-1}$  at  $\sqrt{s} = 7 \text{ TeV}$ . A pronounced resonance peak, with a statistical significance of  $9.7\sigma$ , is observed in the distribution of the invariant mass of four leptons with mass and width consistent with expectations for  $Z$  boson decays. The event yields, branching fraction, and cross section reported here are defined by phase space restrictions on the leptons, namely,  $80 < m_{4\ell} < 100 \text{ GeV}$ , where  $m_{4\ell}$  is the invariant mass of the four leptons, and  $m_{\ell\ell} > 4 \text{ GeV}$  for all pairs of leptons, where  $m_{\ell\ell}$  is the two-lepton invariant mass. We observe 28 events, in agreement with the expectation of  $30.0 \pm 2.6$  events, comprised of  $29.4 \pm 2.6$   $Z \rightarrow 4\ell$  events and  $0.6 \pm 0.2$  events from backgrounds. The measured branching fraction is  $\mathcal{B}(Z \rightarrow 4\ell) = (4.2_{-0.8}^{+0.9} (\text{stat.}) \pm 0.2 (\text{syst.})) \times 10^{-6}$ , in agreement with the standard model prediction of  $4.45 \times 10^{-6}$ . The measured cross section times branching fraction is  $\sigma(pp \rightarrow Z) \mathcal{B}(Z \rightarrow 4\ell) = 112_{-20}^{+23} (\text{stat.})_{-5}^{+7} (\text{syst.})_{-2}^{+3} (\text{lumi.}) \text{ fb}^{-1}$ , also consistent with the standard model prediction of 120 fb. The four-lepton mass peak arising from  $Z \rightarrow 4\ell$  decays provides a calibration channel for the Higgs boson search in the  $H \rightarrow ZZ \rightarrow 4\ell$  decay mode.

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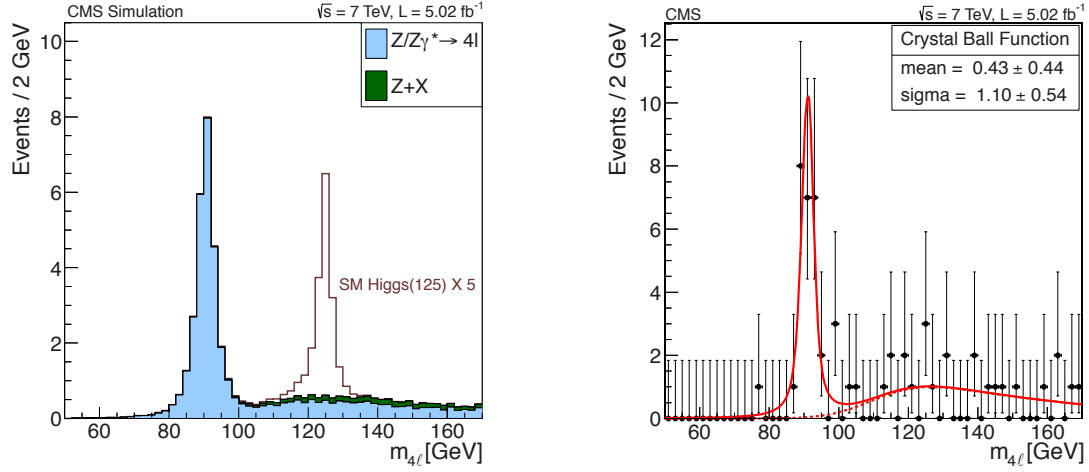


Figure 3: (Left) Four-lepton mass distribution in simulation for  $pp \rightarrow 4\ell$ , without the Higgs boson (light shaded histogram),  $Z + X$  background (dark shaded histogram), and  $pp \rightarrow H \rightarrow ZZ \rightarrow 4\ell$  for a Higgs boson mass  $m_H = 125$  GeV. The three contributions are stacked. The standard model cross section for the Higgs boson is scaled up by a factor of 5. (Right) Four-lepton mass distribution with data represented by the points with error bars. The three final states,  $4e$ ,  $4\mu$ , and  $2e2\mu$ , are combined. The solid line represents a simultaneous fit to the background and Z boson peak.

FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); MoER, SF0690030s09 and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MSI (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MON, RosAtom, RAS and RFBR (Russia); MSTB (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); ThEP, IPST and NECTEC (Thailand); TUBITAK and TAEK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

## References

- [1] ALEPH Collaboration, “Charged particle pair production associated with a lepton pair in Z decays: Indication of an excess in the tau channel”, *Phys. Lett. B* **263** (1991) 112, doi:10.1016/0370-2693(91)91716-9.
- [2] OPAL Collaboration, “A Test of higher order electroweak theory in  $Z^0$  decays to two

- leptons with an associated pair of charged particles”, *Phys. Lett. B* **287** (1992) 389, doi:10.1016/0370-2693(92)91001-P.
- [3] DELPHI Collaboration, “Search for  $Z^0$  decays to two leptons and a charged particle - anti-particle pair”, *Nucl. Phys. B* **403** (1993) 3, doi:10.1016/0550-3213(93)90027-M.
- [4] L3 Collaboration, “A Study of four fermion processes at LEP”, *Phys. Lett. B* **321** (1994) 283, doi:10.1016/0370-2693(94)90478-2.
- [5] CMS Collaboration, “Relative Contributions of t- and s-Channels to the  $ZZ \rightarrow 4\mu$  Process”, CMS Note CMS NOTE-2006/057, (2006).
- [6] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [7] A. Pukhov, E. Boos, M. Dubinin et al., “CompHEP: A Package for evaluation of Feynman diagrams and integration over multiparticle phase space”, (1999). arXiv:hep-ph/9908288.
- [8] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with Parton Shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070.
- [9] Particle Data Group, K. Nakamura, et al., “Review of particle physics”, *J. Phys. G* **37** (2010) 075021, doi:10.1088/0954-3899/37/7A/075021.
- [10] CMS Collaboration, “Search for the Standard Model Higgs Boson in the Decay Channel  $H \rightarrow ZZ \rightarrow 4\ell$  in  $pp$  Collisions at  $\sqrt{s} = 7$  TeV”, *Phys. Rev. Lett.* **108** (2012) 111804, doi:10.1103/PhysRevLett.108.111804.
- [11] CMS Collaboration, “Performance of CMS muon reconstruction in  $pp$  collision events at  $\sqrt{s} = 7$  TeV”, (2012). arXiv:1206.4071. Submitted to the Journal of Instrumentation.
- [12] CMS Collaboration, “Electron Reconstruction and Identification at  $\sqrt{s} = 7$  TeV”, CMS Physics Analysis Summary CMS-PAS-EGM-10-004, (2010).
- [13] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30, doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [14] ATLAS and CMS Collaborations, LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, ATL-PHYS-PUB-2011-11/CMS-NOTE-2011/005, (2011).
- [15] R. Gavin, Y. Li, F. Petriello et al., “FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order”, *Comput. Phys. Commun.* **182** (2011) 2388, doi:10.1016/j.cpc.2011.06.008.
- [16] CMS Collaboration, “Measurement of the Inclusive W and Z Production Cross Sections in  $pp$  Collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132.
- [17] CMS Collaboration, “Absolute Calibration of the CMS Luminosity Measurement: Summer 2011 Update”, CMS Physics Analysis Summary CMS-PAS-EWK-11-001, (2011).

- 
- [18] ATLAS Collaboration, "Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC", *Phys. Lett. B* **716** (2012) 1, doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [19] M. J. Oreglia, "Study of the Reactions Psi-Prime Meson to Gamma, Gamma, Psi", Ph.D. Thesis, Stanford University, Dissertation Abstracts International, Volume 41-11, (1981).

## A The CMS Collaboration

### **Yerevan Physics Institute, Yerevan, Armenia**

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

### **Institut für Hochenergiephysik der OeAW, Wien, Austria**

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan<sup>1</sup>, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler<sup>1</sup>, W. Kiesenhofer, V. Knünz, M. Krammer<sup>1</sup>, D. Liko, I. Mikulec, M. Pernicka<sup>†</sup>, B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz<sup>1</sup>

### **National Centre for Particle and High Energy Physics, Minsk, Belarus**

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

### **Universiteit Antwerpen, Antwerpen, Belgium**

S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

### **Vrije Universiteit Brussel, Brussel, Belgium**

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

### **Université Libre de Bruxelles, Bruxelles, Belgium**

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, C. Vander Velde, P. Vanlaer, J. Wang

### **Ghent University, Ghent, Belgium**

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

### **Université Catholique de Louvain, Louvain-la-Neuve, Belgium**

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco<sup>2</sup>, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

### **Université de Mons, Mons, Belgium**

N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

### **Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil**

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

### **Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil**

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

### **Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil**

C.A. Bernardes<sup>3</sup>, F.A. Dias<sup>4</sup>, T.R. Fernandez Perez Tomei, E.M. Gregores<sup>3</sup>, C. Lagana, F. Marinho, P.G. Mercadante<sup>3</sup>, S.F. Novaes, Sandra S. Padula

### **Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria**

V. Genchev<sup>5</sup>, P. Iaydjiev<sup>5</sup>, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

**University of Sofia, Sofia, Bulgaria**

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

**Institute of High Energy Physics, Beijing, China**

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

**State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China**

C. Asawatangkuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, B. Zhu, W. Zou

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

**Technical University of Split, Split, Croatia**

N. Godinovic, D. Lelas, R. Plestina<sup>6</sup>, D. Polic, I. Puljak<sup>5</sup>

**University of Split, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

**University of Cyprus, Nicosia, Cyprus**

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

**Charles University, Prague, Czech Republic**

M. Finger, M. Finger Jr.

**Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt**

Y. Assran<sup>7</sup>, S. Elgammal<sup>8</sup>, A. Ellithi Kamel<sup>9</sup>, M.A. Mahmoud<sup>10</sup>, A. Radi<sup>11,12</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, G. Fedi, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

**Lappeenranta University of Technology, Lappeenranta, Finland**

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

**DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France**

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

**Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France**

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj<sup>13</sup>, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

**Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France**

J.-L. Agram<sup>14</sup>, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte<sup>14</sup>, F. Drouhin<sup>14</sup>, C. Ferro, J.-C. Fontaine<sup>14</sup>, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France**

F. Fassi, D. Mercier

**Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France**

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici<sup>5</sup>, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier, S. Viret

**Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>15</sup>

**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov<sup>16</sup>

**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

**RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany**

M. Bontenackels, V. Cherepanov, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz<sup>17</sup>, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann<sup>17</sup>, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt<sup>17</sup>, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

**University of Hamburg, Hamburg, Germany**

C. Autermann, V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Høing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

**Institut für Experimentelle Kernphysik, Karlsruhe, Germany**

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff<sup>5</sup>, C. Hackstein, F. Hartmann, T. Hauth<sup>5</sup>, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov<sup>16</sup>, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

**Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece**

G. Daskalakis, T. Gerasis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

**University of Athens, Athens, Greece**

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas<sup>5</sup>, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

**KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary**

G. Bencze, C. Hajdu<sup>5</sup>, P. Hidas, D. Horvath<sup>18</sup>, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>19</sup>

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

**University of Debrecen, Debrecen, Hungary**

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

**Panjab University, Chandigarh, India**

M. Bansal, S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

**University of Delhi, Delhi, India**

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

**Saha Institute of Nuclear Physics, Kolkata, India**

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

**Bhabha Atomic Research Centre, Mumbai, India**

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty<sup>5</sup>, L.M. Pant, P. Shukla

**Tata Institute of Fundamental Research - EHEP, Mumbai, India**

T. Aziz, S. Ganguly, M. Guchait<sup>20</sup>, M. Maity<sup>21</sup>, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

**Tata Institute of Fundamental Research - HECR, Mumbai, India**

S. Banerjee, S. Dugad

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**

H. Arfaei, H. Bakhshiansohi<sup>22</sup>, S.M. Etesami<sup>23</sup>, A. Fahim<sup>22</sup>, M. Hashemi, H. Hesari, A. Jafari<sup>22</sup>, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh<sup>24</sup>, M. Zeinali<sup>23</sup>

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**

M. Abbrescia<sup>a,b</sup>, L. Barbone<sup>a,b</sup>, C. Calabria<sup>a,b,5</sup>, S.S. Chhibra<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>,



N. De Filippis<sup>a,c,5</sup>, M. De Palma<sup>a,b</sup>, L. Fiore<sup>a</sup>, G. Iaselli<sup>a,c</sup>, L. Lusito<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, B. Marangelli<sup>a,b</sup>, S. My<sup>a,c</sup>, S. Nuzzo<sup>a,b</sup>, N. Pacifico<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, G. Selvaggi<sup>a,b</sup>, L. Silvestris<sup>a</sup>, G. Singh<sup>a,b</sup>, R. Venditti<sup>a,b</sup>, G. Zito<sup>a</sup>

**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**

G. Abbiendi<sup>a</sup>, A.C. Benvenuti<sup>a</sup>, D. Bonacorsi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b,5</sup>, P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, M. Meneghelli<sup>a,b,5</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, F. Odorici<sup>a</sup>, A. Perrotta<sup>a</sup>, F. Primavera<sup>a,b</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, R. Travaglini<sup>a,b</sup>

**INFN Sezione di Catania <sup>a</sup>, Università di Catania <sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b</sup>, G. Cappello<sup>a,b</sup>, M. Chiorboli<sup>a,b</sup>, S. Costa<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze <sup>a</sup>, Università di Firenze <sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, S. Frosali<sup>a,b</sup>, E. Gallo<sup>a</sup>, S. Gonzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, G. Sguazzoni<sup>a</sup>, A. Tropiano<sup>a,5</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, S. Colafranceschi<sup>25</sup>, F. Fabbri, D. Piccolo

**INFN Sezione di Genova <sup>a</sup>, Università di Genova <sup>b</sup>, Genova, Italy**

P. Fabbriatore<sup>a</sup>, R. Musenich<sup>a</sup>

**INFN Sezione di Milano-Bicocca <sup>a</sup>, Università di Milano-Bicocca <sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a,b,5</sup>, F. De Guio<sup>a,b</sup>, L. Di Matteo<sup>a,b,5</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a,5</sup>, A. Ghezzi<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, A. Martelli<sup>a,b</sup>, A. Massironi<sup>a,b,5</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Ragazzi<sup>a,b</sup>, N. Redaelli<sup>a</sup>, S. Sala<sup>a</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli <sup>a</sup>, Università di Napoli "Federico II" <sup>b</sup>, Napoli, Italy**

S. Buontempo<sup>a</sup>, C.A. Carrillo Montoya<sup>a,5</sup>, N. Cavallo<sup>a,26</sup>, A. De Cosa<sup>a,b,5</sup>, O. Dogangun<sup>a,b</sup>, F. Fabozzi<sup>a,26</sup>, A.O.M. Iorio<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,27</sup>, M. Merola<sup>a,b</sup>, P. Paolucci<sup>a,5</sup>

**INFN Sezione di Padova <sup>a</sup>, Università di Padova <sup>b</sup>, Università di Trento (Trento) <sup>c</sup>, Padova, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a,5</sup>, M. Bellato<sup>a</sup>, D. Bisello<sup>a,b</sup>, A. Branca<sup>a,b,5</sup>, R. Carlin<sup>a,b</sup>, P. Checchia<sup>a</sup>, T. Dorigo<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, K. Kanishchev<sup>a,c</sup>, S. Lacaprara<sup>a</sup>, I. Lazzizzera<sup>a,c</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, J. Pazzini<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, E. Torassa<sup>a</sup>, M. Tosi<sup>a,b,5</sup>, S. Vanini<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia <sup>a</sup>, Università di Pavia <sup>b</sup>, Pavia, Italy**

M. Gabusi<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Torre<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia <sup>a</sup>, Università di Perugia <sup>b</sup>, Perugia, Italy**

M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, A. Lucaroni<sup>a,b,5</sup>, G. Mantovani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Nappi<sup>a,b</sup>, F. Romeo<sup>a,b</sup>, A. Saha<sup>a</sup>, A. Santocchia<sup>a,b</sup>, S. Taroni<sup>a,b,5</sup>

**INFN Sezione di Pisa <sup>a</sup>, Università di Pisa <sup>b</sup>, Scuola Normale Superiore di Pisa <sup>c</sup>, Pisa, Italy**

P. Azzurri<sup>a,c</sup>, G. Bagliesi<sup>a</sup>, J. Bernardini<sup>a</sup>, T. Boccali<sup>a</sup>, G. Broccolo<sup>a,c</sup>, R. Castaldi<sup>a</sup>, R.T. D'Agnolo<sup>a,c</sup>, R. Dell'Orso<sup>a</sup>, F. Fiori<sup>a,b,5</sup>, L. Foà<sup>a,c</sup>, A. Giassi<sup>a</sup>, A. Kraan<sup>a</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, L. Martini<sup>a,28</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, A.T. Serban<sup>a,29</sup>, P. Spagnolo<sup>a</sup>, P. Squillacioti<sup>a,5</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b,5</sup>, A. Venturi<sup>a,5</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma <sup>a</sup>, Università di Roma <sup>b</sup>, Roma, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, D. Del Re<sup>a,b,5</sup>, M. Diemoz<sup>a</sup>, M. Grassi<sup>a,b,5</sup>, E. Longo<sup>a,b</sup>,

P. Meridiani<sup>a,5</sup>, F. Micheli<sup>a,b</sup>, S. Nourbakhsh<sup>a,b</sup>, G. Organtini<sup>a,b</sup>, R. Paramatti<sup>a</sup>, S. Rahatlou<sup>a,b</sup>, M. Sigamani<sup>a</sup>, L. Soffi<sup>a,b</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Università del Piemonte Orientale (Novara) <sup>c</sup>, Torino, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, M. Costa<sup>a,b</sup>, N. Demaria<sup>a</sup>, C. Mariotti<sup>a,5</sup>, S. Maselli<sup>a</sup>, G. Mazza<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, M. Musich<sup>a,5</sup>, M.M. Obertino<sup>a,c</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, A. Potenza<sup>a,b</sup>, A. Romero<sup>a,b</sup>, R. Sacchi<sup>a,b</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>, A. Vilela Pereira<sup>a</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, V. Candelise<sup>a,b</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, B. Gobbo<sup>a</sup>, M. Marone<sup>a,b,5</sup>, D. Montanino<sup>a,b,5</sup>, A. Penzo<sup>a</sup>, A. Schizzi<sup>a,b</sup>

**Kangwon National University, Chunchon, Korea**

S.G. Heo, T.Y. Kim, S.K. Nam

**Kyungpook National University, Daegu, Korea**

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

**Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea**

J.Y. Kim, Zero J. Kim, S. Song

**Korea University, Seoul, Korea**

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

**University of Seoul, Seoul, Korea**

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

**Sungkyunkwan University, Suwon, Korea**

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

**Vilnius University, Vilnius, Lithuania**

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

**Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico**

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

**Universidad Iberoamericana, Mexico City, Mexico**

S. Carrillo Moreno, F. Vazquez Valencia

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

H.A. Salazar Ibarguen

**Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico**

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

**National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan**

M. Ahmad, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

**National Centre for Nuclear Research, Swierk, Poland**

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

**Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland**

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

**Joint Institute for Nuclear Research, Dubna, Russia**

I. Belotelov, M. Gavrilenko, I. Golutvin, A. Kamenev, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov<sup>5</sup>, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

**Moscow State University, Moscow, Russia**

A. Belyaev, E. Boos, M. Dubinin<sup>4</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva<sup>†</sup>, V. Savrin, A. Snigirev

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin<sup>5</sup>, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

**University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia**

P. Adzic<sup>30</sup>, M. Djordjevic, M. Ekmedzic, D. Krpic<sup>30</sup>, J. Milosevic

**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo

Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, G. Codispoti, J.F. de Trocóniz

**Universidad de Oviedo, Oviedo, Spain**

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

**Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain**

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini<sup>31</sup>, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet<sup>6</sup>, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi<sup>32</sup>, T. Rommerskirchen, C. Rovelli<sup>33</sup>, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas<sup>34</sup>, D. Spiga, A. Tsiros, G.I. Veres<sup>19</sup>, J.R. Vlimant, H.K. Wöhri, S.D. Worm<sup>35</sup>, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille<sup>36</sup>

**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli<sup>37</sup>, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov<sup>38</sup>, B. Stieger, M. Takahashi, L. Tauscher<sup>†</sup>, A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

**Universität Zürich, Zurich, Switzerland**

C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

**National Central University, Chung-Li, Taiwan**

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

**Cukurova University, Adana, Turkey**

A. Adiguzel, M.N. Bakirci<sup>39</sup>, S. Cerci<sup>40</sup>, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar<sup>41</sup>, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk<sup>42</sup>, A. Polatoz, K. Sogut<sup>43</sup>, D. Sunar Cerci<sup>40</sup>, B. Tali<sup>40</sup>, H. Topakli<sup>39</sup>, L.N. Vergili, M. Vergili

**Middle East Technical University, Physics Department, Ankara, Turkey**

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

E. Gülmez, B. Isildak<sup>44</sup>, M. Kaya<sup>45</sup>, O. Kaya<sup>45</sup>, S. Ozkorucuklu<sup>46</sup>, N. Sonmez<sup>47</sup>

**Istanbul Technical University, Istanbul, Turkey**

K. Cankocak

**National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine**

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold<sup>35</sup>, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

L. Basso<sup>48</sup>, K.W. Bell, A. Belyaev<sup>48</sup>, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

**Imperial College, London, United Kingdom**

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko<sup>38</sup>, A. Papageorgiou, J. Pela<sup>5</sup>, M. Pesaresi, K. Petridis, M. Pioppi<sup>49</sup>, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp<sup>†</sup>, A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

**Brunel University, Uxbridge, United Kingdom**

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

**Baylor University, Waco, USA**

K. Hatakeyama, H. Liu, T. Scarborough

**The University of Alabama, Tuscaloosa, USA**

O. Charaf, C. Henderson, P. Rumerio

**Boston University, Boston, USA**

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

**Brown University, Providence, USA**

J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

**University of California, Davis, Davis, USA**

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

**University of California, Los Angeles, Los Angeles, USA**

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein<sup>†</sup>, J. Tucker, V. Valuev, M. Weber

**University of California, Riverside, Riverside, USA**

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng<sup>50</sup>, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

**University of California, San Diego, La Jolla, USA**

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech<sup>51</sup>, F. Würthwein, A. Yagil, J. Yoo

**University of California, Santa Barbara, Santa Barbara, USA**

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

**California Institute of Technology, Pasadena, USA**

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

B. Akgun, V. Azzolini, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

**University of Colorado at Boulder, Boulder, USA**

J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luigi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

**Cornell University, Ithaca, USA**

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

**Fairfield University, Fairfield, USA**

D. Winn

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko<sup>52</sup>, C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic<sup>53</sup>, G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

**Florida International University, Miami, USA**

V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

**Florida State University, Tallahassee, USA**

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

**Florida Institute of Technology, Melbourne, USA**

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

**University of Illinois at Chicago (UIC), Chicago, USA**

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

**The University of Iowa, Iowa City, USA**

U. Akgun, E.A. Albayrak, B. Bilki<sup>54</sup>, W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya<sup>55</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

**Johns Hopkins University, Baltimore, USA**

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

**The University of Kansas, Lawrence, USA**

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

**Kansas State University, Manhattan, USA**

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

**Lawrence Livermore National Laboratory, Livermore, USA**

J. Gronberg, D. Lange, D. Wright

**University of Maryland, College Park, USA**

A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,

T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

**Massachusetts Institute of Technology, Cambridge, USA**

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar<sup>56</sup>, W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

**University of Minnesota, Minneapolis, USA**

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

**University of Mississippi, Oxford, USA**

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

**University of Nebraska-Lincoln, Lincoln, USA**

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

**State University of New York at Buffalo, Buffalo, USA**

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

**Northwestern University, Evanston, USA**

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

**University of Notre Dame, Notre Dame, USA**

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

**The Ohio State University, Columbus, USA**

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

**Princeton University, Princeton, USA**

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

**University of Puerto Rico, Mayaguez, USA**

J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

**Purdue University, West Lafayette, USA**

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng



**Purdue University Calumet, Hammond, USA**

S. Guragain, N. Parashar

**Rice University, Houston, USA**

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

**University of Rochester, Rochester, USA**

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

**The Rockefeller University, New York, USA**

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

**Rutgers, the State University of New Jersey, Piscataway, USA**

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

**University of Tennessee, Knoxville, USA**

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

**Texas A&M University, College Station, USA**

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon<sup>57</sup>, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

**Texas Tech University, Lubbock, USA**

N. Akchurin, J. Damgov, P.R. Duderod, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

**Vanderbilt University, Nashville, USA**

E. Appelt, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

**University of Virginia, Charlottesville, USA**

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

**Wayne State University, Detroit, USA**

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

**University of Wisconsin, Madison, USA**

M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

3: Also at Universidade Federal do ABC, Santo Andre, Brazil

4: Also at California Institute of Technology, Pasadena, USA

- 5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- 6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- 7: Also at Suez Canal University, Suez, Egypt
- 8: Also at Zewail City of Science and Technology, Zewail, Egypt
- 9: Also at Cairo University, Cairo, Egypt
- 10: Also at Fayoum University, El-Fayoum, Egypt
- 11: Also at British University in Egypt, Cairo, Egypt
- 12: Now at Ain Shams University, Cairo, Egypt
- 13: Also at National Centre for Nuclear Research, Swierk, Poland
- 14: Also at Université de Haute-Alsace, Mulhouse, France
- 15: Now at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Sharif University of Technology, Tehran, Iran
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 25: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- 26: Also at Università della Basilicata, Potenza, Italy
- 27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
- 30: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 31: Also at University of California, Los Angeles, Los Angeles, USA
- 32: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- 33: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
- 34: Also at University of Athens, Athens, Greece
- 35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 36: Also at The University of Kansas, Lawrence, USA
- 37: Also at Paul Scherrer Institut, Villigen, Switzerland
- 38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 39: Also at Gaziosmanpasa University, Tokat, Turkey
- 40: Also at Adiyaman University, Adiyaman, Turkey
- 41: Also at Izmir Institute of Technology, Izmir, Turkey
- 42: Also at The University of Iowa, Iowa City, USA
- 43: Also at Mersin University, Mersin, Turkey
- 44: Also at Ozyegin University, Istanbul, Turkey
- 45: Also at Kafkas University, Kars, Turkey
- 46: Also at Suleyman Demirel University, Isparta, Turkey
- 47: Also at Ege University, Izmir, Turkey
- 48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 49: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 50: Also at University of Sydney, Sydney, Australia
- 51: Also at Utah Valley University, Orem, USA

52: Also at Institute for Nuclear Research, Moscow, Russia

53: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

54: Also at Argonne National Laboratory, Argonne, USA

55: Also at Erzincan University, Erzincan, Turkey

56: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

57: Also at Kyungpook National University, Daegu, Korea